# Impact of full JLab 6 GeV DIS data on CTEQ-JLab (CJ) PDFs & nuclear effects


by

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University of Virginia

Hampton University — The Standard of Excellence

Jefferson Lab — Thomas Jefferson National Accelerator Facility

SpinQuest

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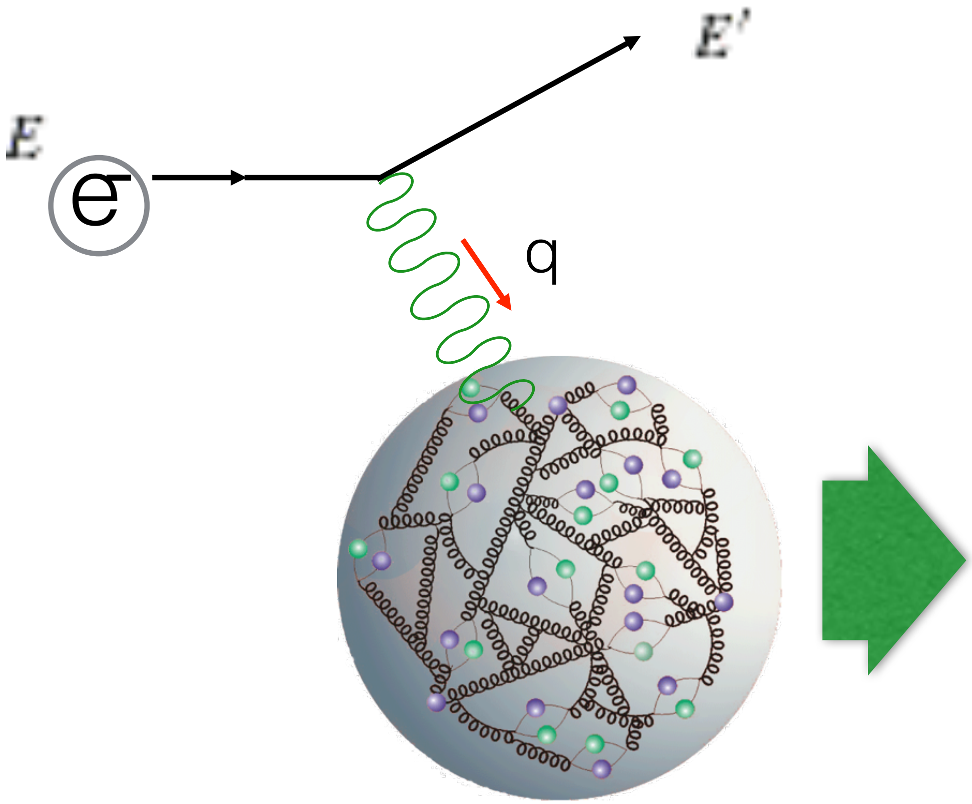
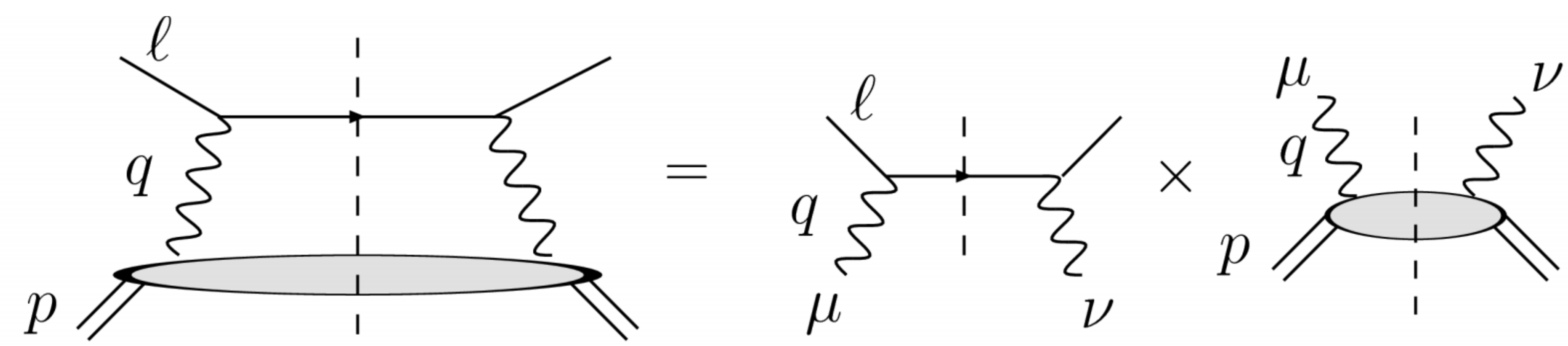
# Outline

- CJ framework for Nucleon
- CJ framework for Deuteron
- Off-Shell variations
- Higher-Twist variations
- JLab 6 GeV data (Kinematics)
- Interplay of observables' dynamics
- F2d/F2n extraction
- Impact of Jlab 6 GeV data on d/u & Off-Shell

# Framework for Nucleon

*Deep inelastic scattering* (DIS)




Cross-Section

$$\frac{d\sigma}{dx dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^4} L_{\mu\nu}(\ell, q) W^{\mu\nu}(p, q)$$

$$L_{\mu\nu} = 2\left(\ell_\mu \ell'_\nu + \ell'_\mu \ell'_\nu - \ell \cdot \ell' g_{\mu\nu}\right)$$

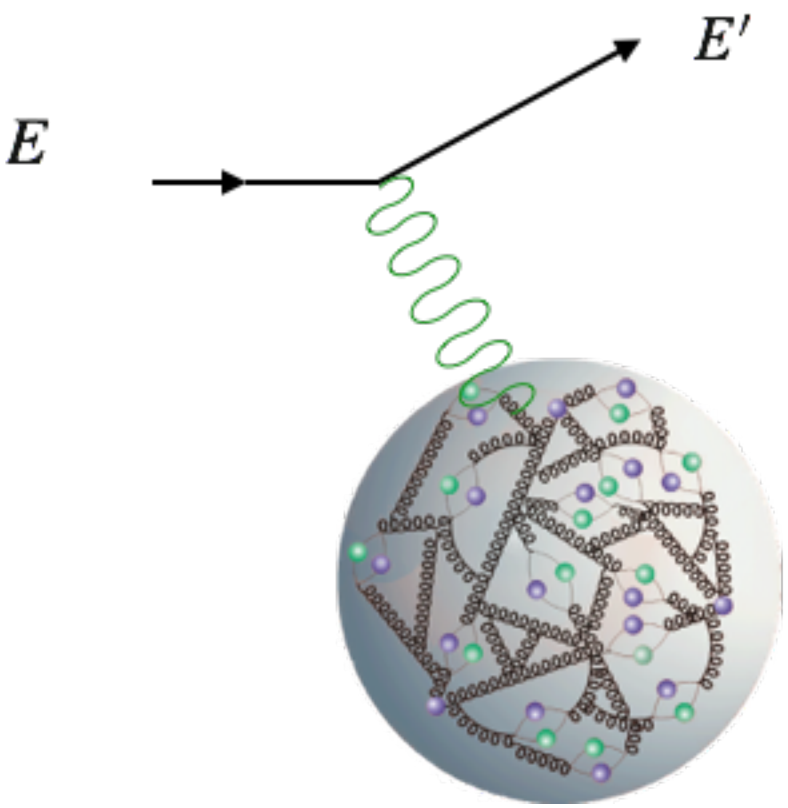
$$\boxed{\begin{aligned}\frac{d\sigma}{dx_B dQ^2} = \frac{4\pi\alpha^2}{x_B Q^4}\Big\{&\left(1 - y - x_B^2 y^2 \frac{M^2}{Q^2}\right) F_2(x_B, Q^2) \\ &+ y^2 x_B F_1(x_B, Q^2) + \left(y - \frac{y^2}{2}\right) x_B F_3(x_B, Q^2)\Big\}\end{aligned}}$$

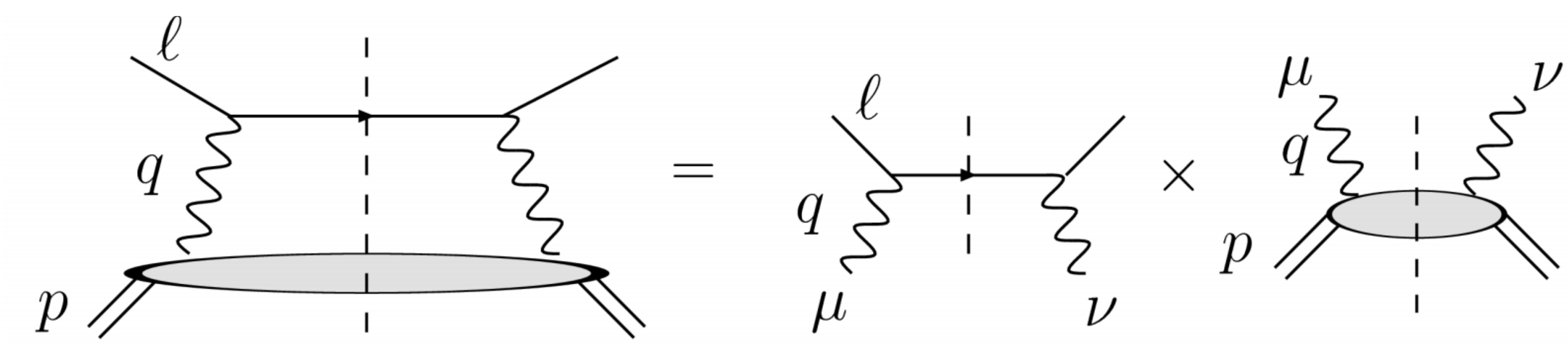
Lorentz invariants

| | | |
|---|---|---|
| $Q^2 = -q^2$ | $x_B = \frac{-q^2}{2p \cdot q}$ | $\nu = \frac{p \cdot q}{\sqrt{p^2}}$ |
| virtuality | Bjorken x | beam energy loss |
| $y = \frac{p \cdot q}{p \cdot \ell}$ | $W^2 = (p + q)^2$ | $s = (p + \ell)^2$ |
| inelasticity | (final state) invariant mass | center-of-mass energy |

# Framework for Nucleon

*Deep inelastic scattering* (DIS)




Cross-Section

$$\frac{d\sigma}{dx_B dQ^2} = \frac{4\pi\alpha^2}{x_B Q^4}\left\{\left(1 - y - x_B^2 y^2 \frac{M^2}{Q^2}\right) F_2(x_B, Q^2) + y^2 x_B F_1(x_B, Q^2) + \left(y - \frac{y^2}{2}\right) x_B F_3(x_B, Q^2)\right\}$$

$$F_2(x, Q^2, p^2) = F_2(x, Q^2)\left(1 + \delta f_2(x, Q^2)\,\frac{p^2 - M^2}{M^2}\right)$$

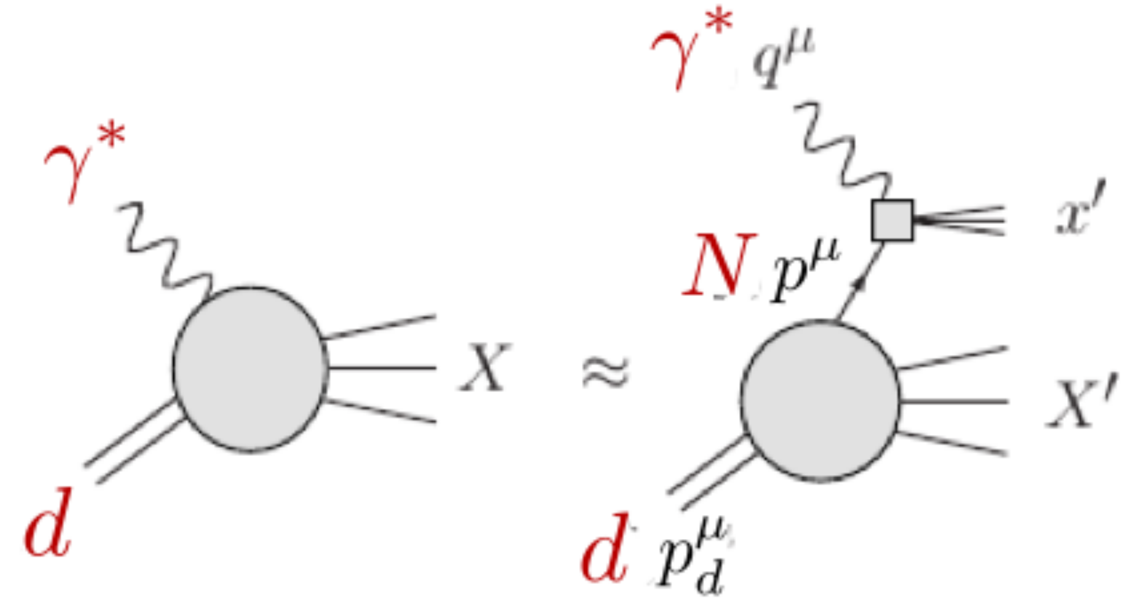
$$\delta f_2(x, Q^2) = \frac{\partial \ln F_2(x, Q^2, p^2)}{\partial \ln p^2},$$

Parton Parameterization

$$xf(x, Q_0^2) = a_0 x^{a_1}(1-x)^{a_2}(1 + a_3\sqrt{x} + a_4 x)$$

# Framework for Deuteron

*Fermi-motion and binding*




- Incoherent scattering from not too fast individual nucleons

- Final State Interactions (FSI) can be neglected

$$F_{2d}(x, Q^2) = \int \frac{dz}{z} dp_T^2 \, \mathcal{K}(z, p^2, \gamma) \, \left|\psi_{N/d}(|\vec{p}\,|)\right|^2 F_{2N}(x/z, Q^2, p^2)$$

kinematic and "flux" factors

Nucleon wave function

structure function of **bound, off-shell nucleon**

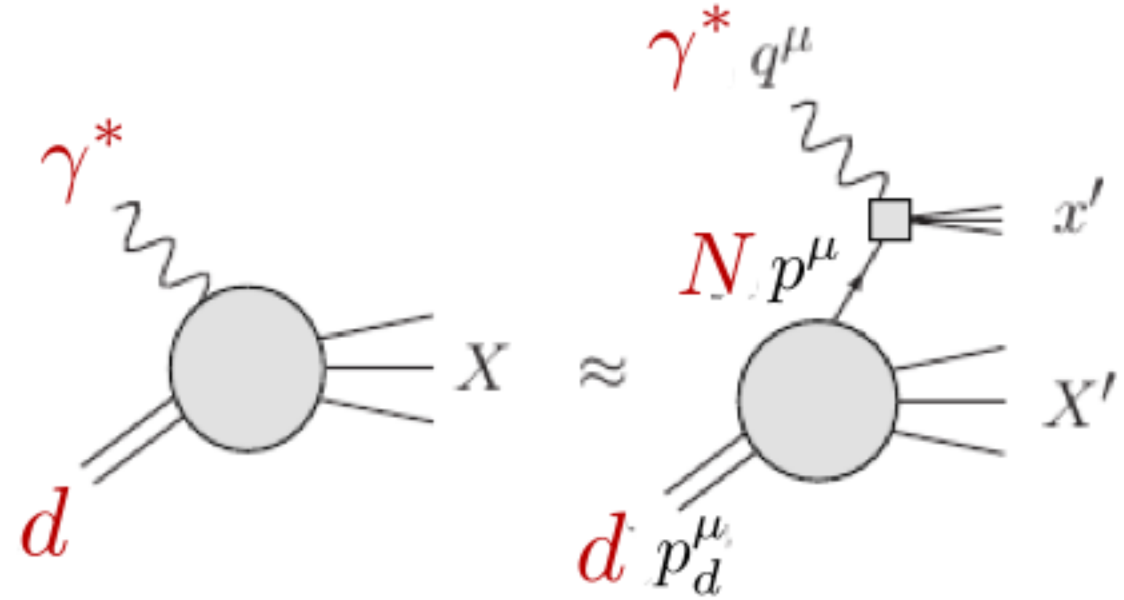
*Momentum fraction of 'd' carried by 'N'*

$$z = \frac{p.q}{p_d.q} \approx 1 + \frac{p_0 + \gamma p_z}{M} \qquad p_0 = M + \epsilon \qquad \epsilon = \epsilon_d - \frac{\vec{p}^2}{2M}$$

At finite $Q^2$, $\gamma = \sqrt{1 + \frac{4x^2p^2}{Q^2}}$

this quantifies how far the nucleon is from the light-cone $\gamma = 1$

# Framework for Deuteron




## *Off Shell corrections*

- Nucleons are bound in the deuteron (but not too much if x not too large)

- Structure Functions are deformed

$$F_{2N}(x,Q^2,p^2) = F_{2N}^{\text{free}}(x,Q^2)\left[1+\frac{p^2-M^2}{M^2}\delta f(x)\right]$$

Free proton, neutron structure function

"offshelll function"

## *CJ15*

- Parameterization inspired by Kulagin, Petti (2007)

$\nu = (p^2 - M^2)/M^2$

$$\delta f(x) = C(x-x_0)(x-x_1)(1+x-x_0)$$

- Generalized parameterizations

$$\delta f(x) = a_0 + a_1 x + a_2 x^2$$

$$\delta f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$$

# CJ15 Off shell variations

- Parameterization inspired by Kulagin, Petti (2007)

$\nu = (p^2 - M^2)/M^2$

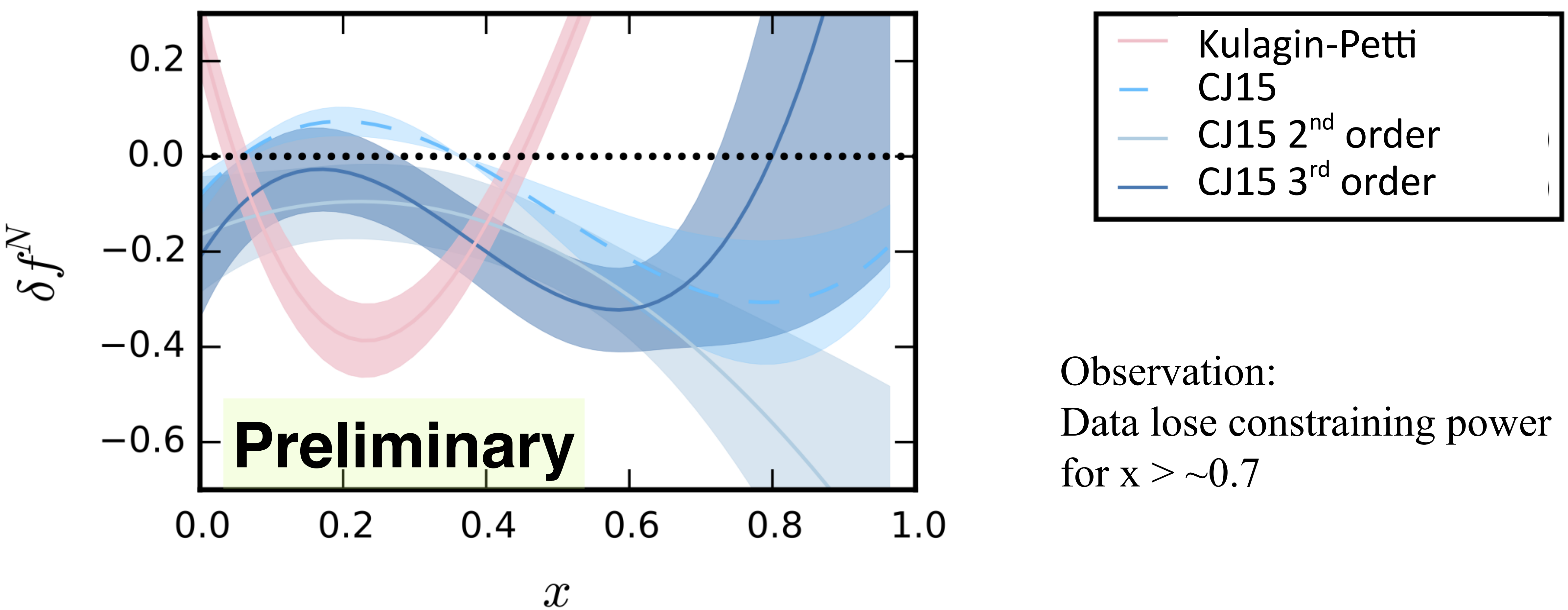
$$\delta f(x) = C(x - x_0)(x - x_1)(1 + x - x_0)$$

fixed by Baryon number sum rul

- Generalized parameterizations

$$\delta f(x) = a_0 + a_1 x + a_2 x^2$$

$$\delta f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$$




Observation:
Data lose constraining power for x > ~0.7

# CJ15 Higher-Twist variations

- Two sets of choices -> 4 combinations

Additive $$F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$$

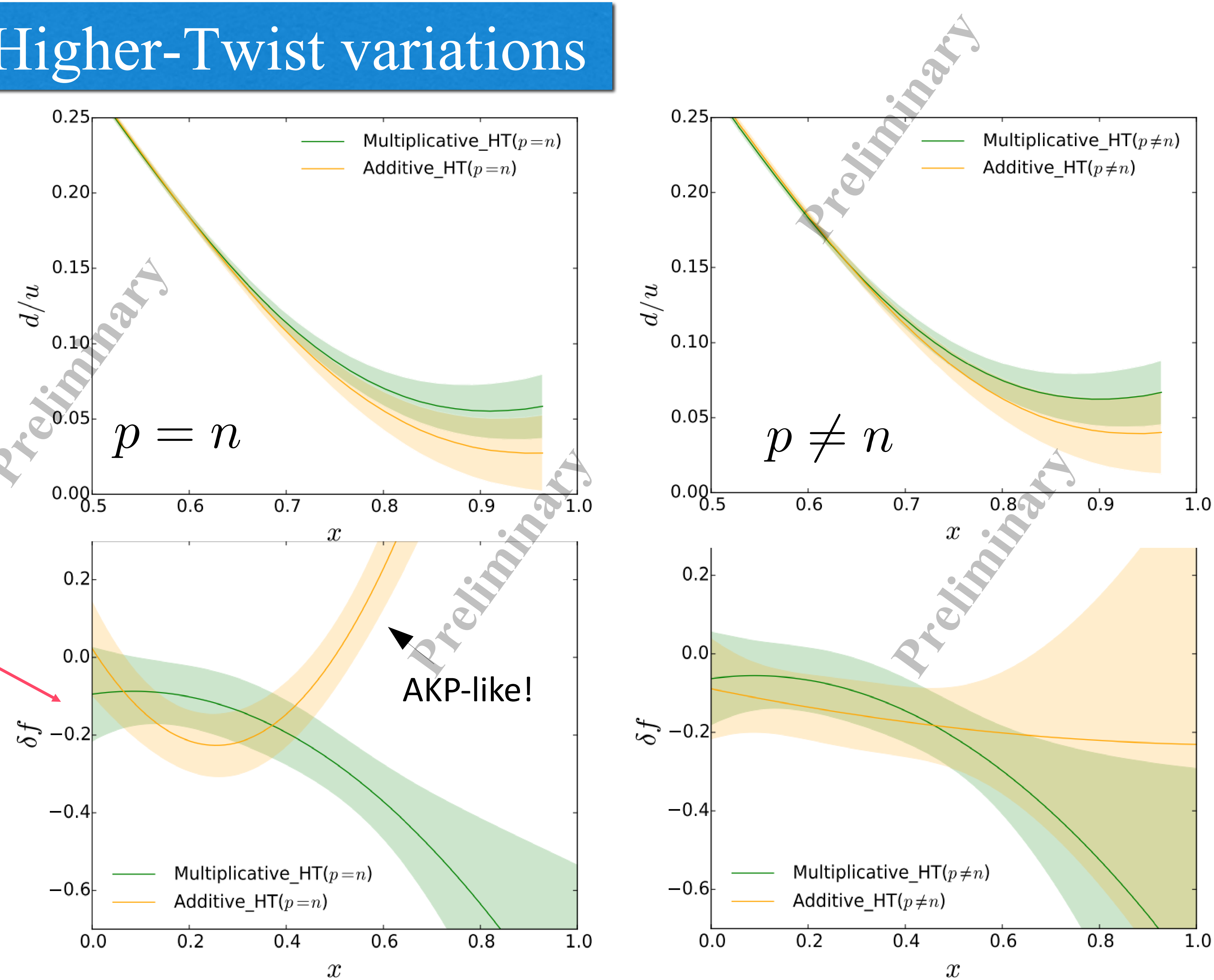
Multiplicative $$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

Iso-Spin

| Symmetric | Asymmetric |
|---|---|
| $H_p(x) = H_n(x)$ | $H_p(x) \neq H_n(x)$ |

$$C(x) = C_1 x^{C_2}(1 + C_3 x) \qquad H(x) = h_1 x^{h_2}(1 + h_3 x)(1 - x)^{h_4}$$

# CJ15 Higher-Twist variations



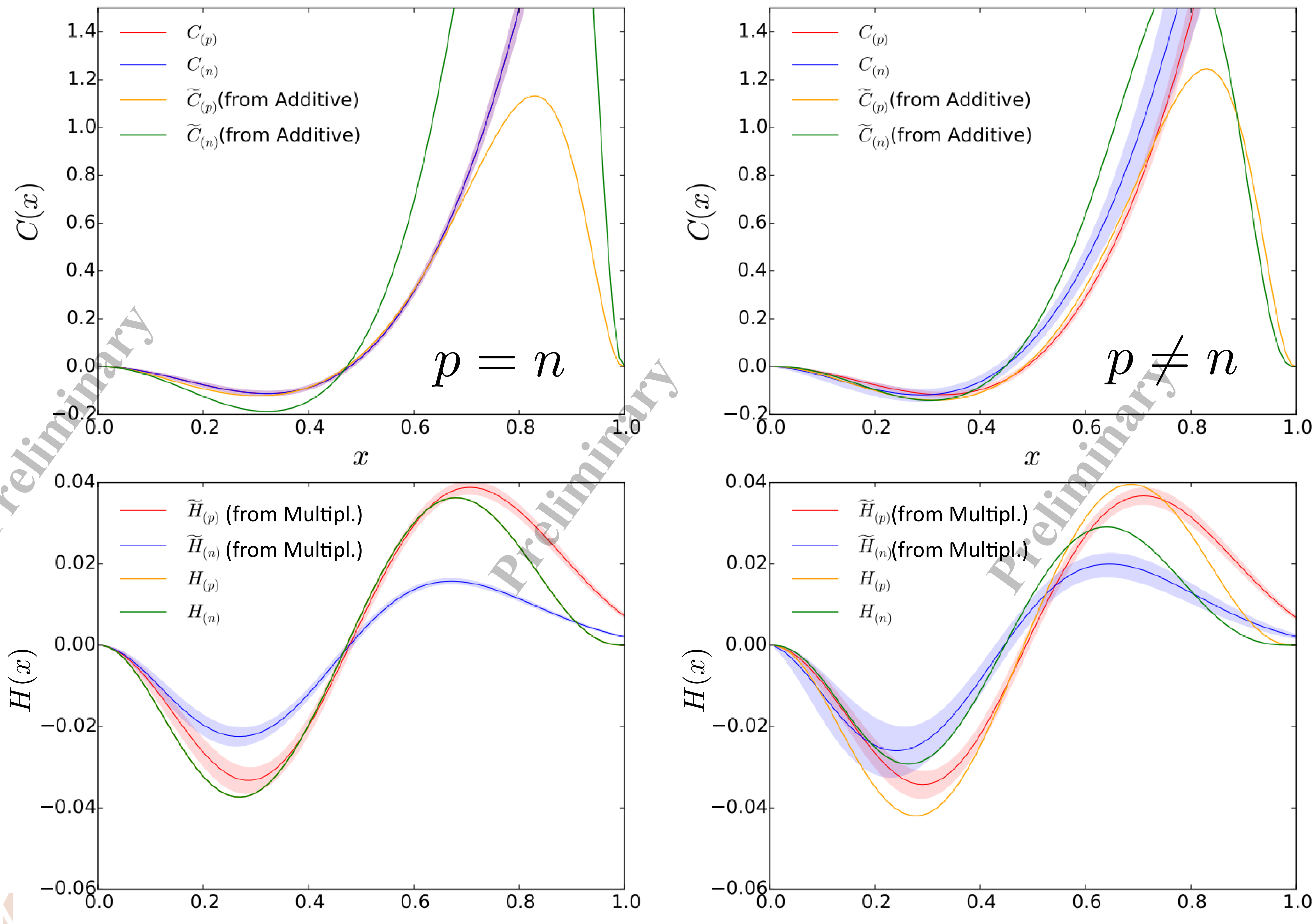

**An agreement with Alekhin + KP (e+d global fits) PRD96 (2017) 054005**

Additive HT
+
$p = n$

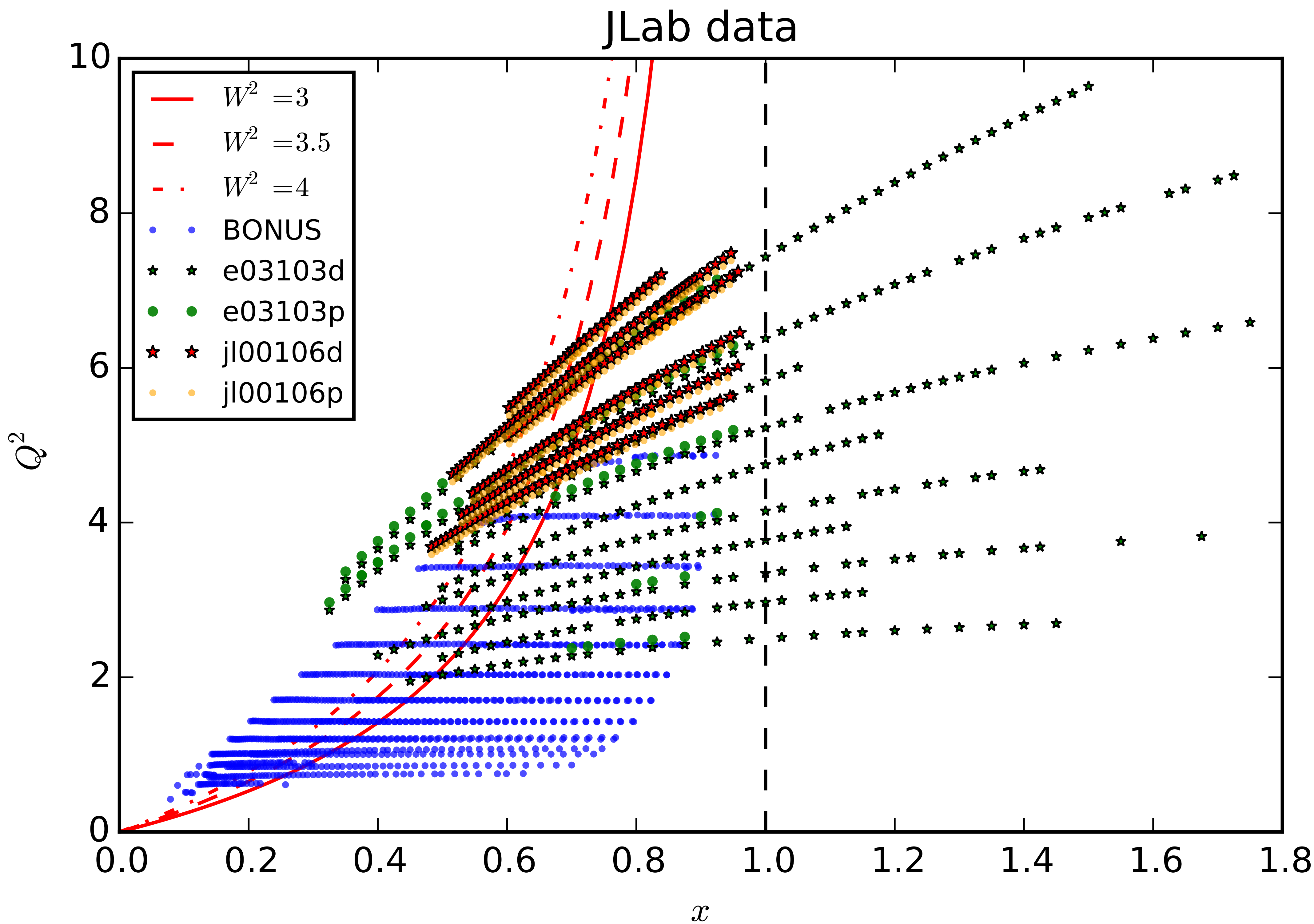


both groups are currently (collaboratively) working on identifying the source of this discrepancy

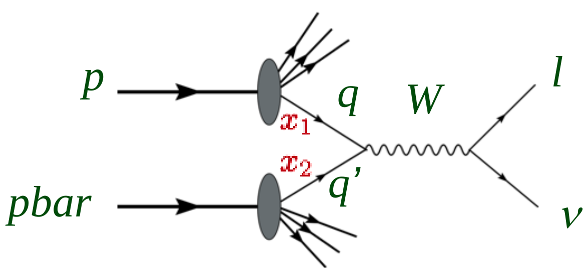
# CJ15 Higher-Twist variations



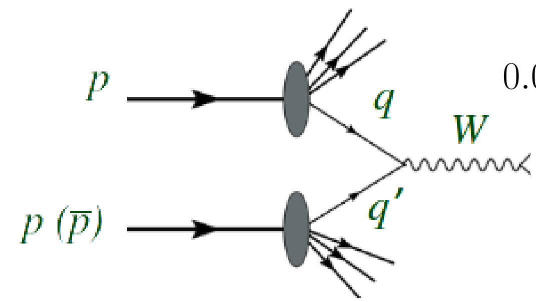
# JLab 6 GeV data (Kinematical Coverage)

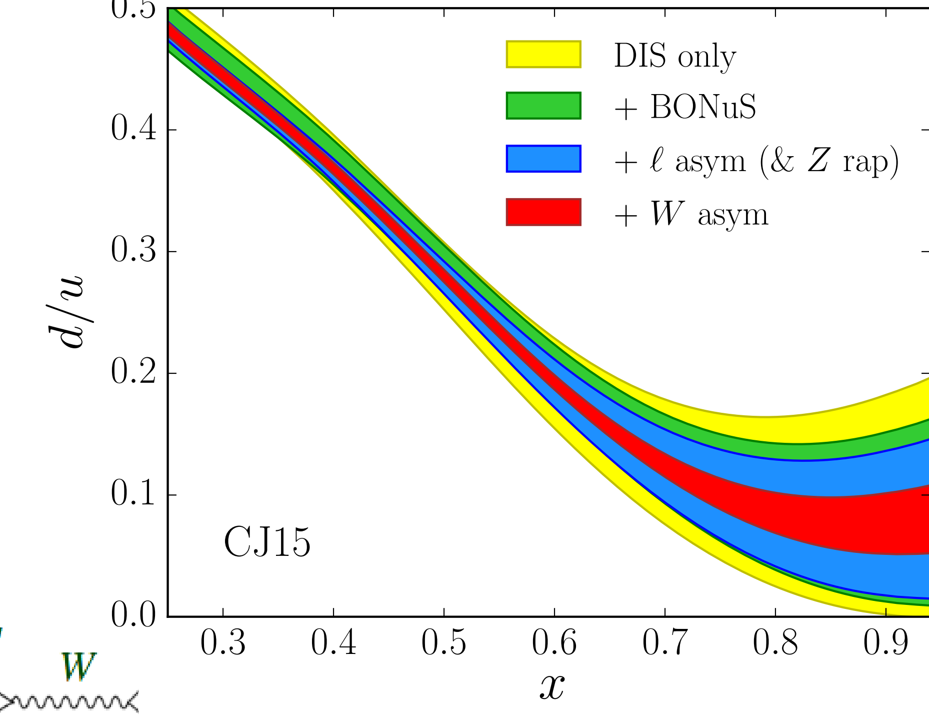


# Interplay of observables

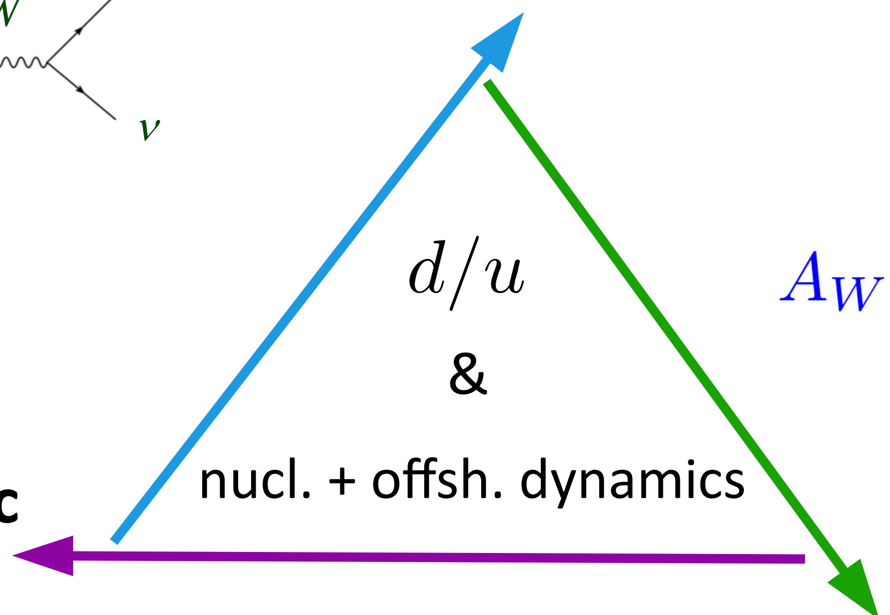



**D0, CDF asymmetries**

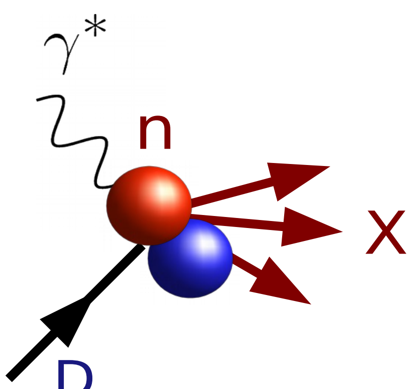



$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

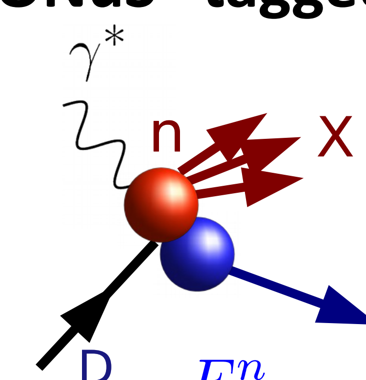



**Deep inelastic deuterium**




$$F_2^d \propto \mathcal{S}_D \otimes \left[ x u_{\rm off}(x) + x d_{\rm off}(x) \right]$$

**"BONuS" tagged neutron target**

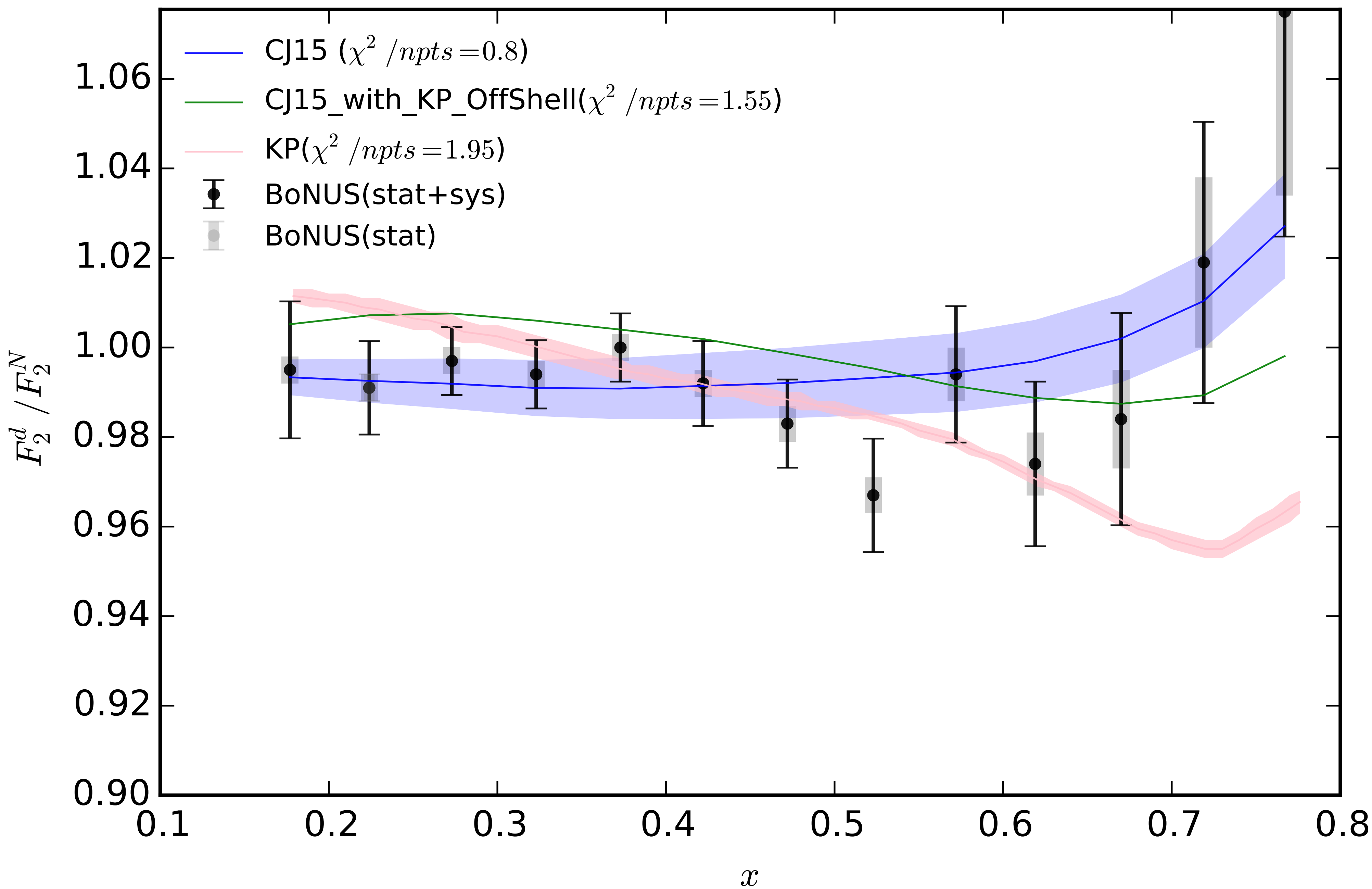



$$\frac{F_2^n}{F_2^d} \propto x u(x) + 4 x d(x)$$

 *Picture Courtesy Alberto Accardi*

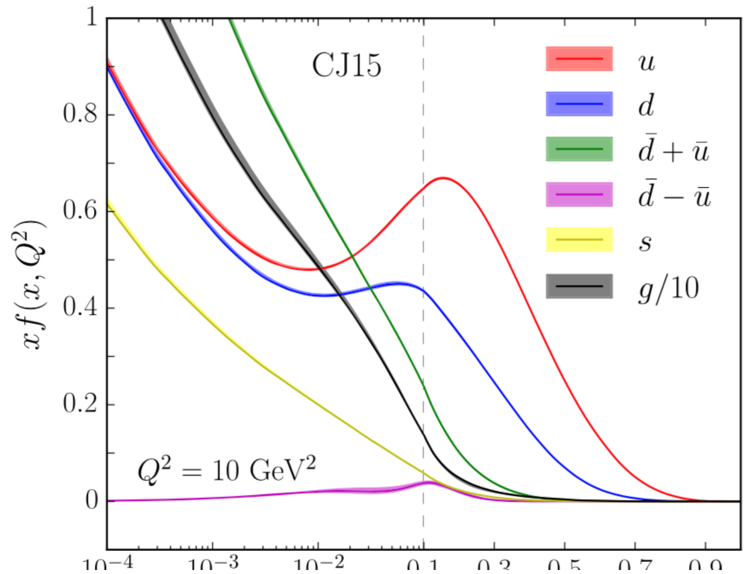
# F2d/F2n extraction

$F_2^d/F_2^N$ calculations from CJ15, KP and BoNUS $F_2^d/F_2^N$ extraction



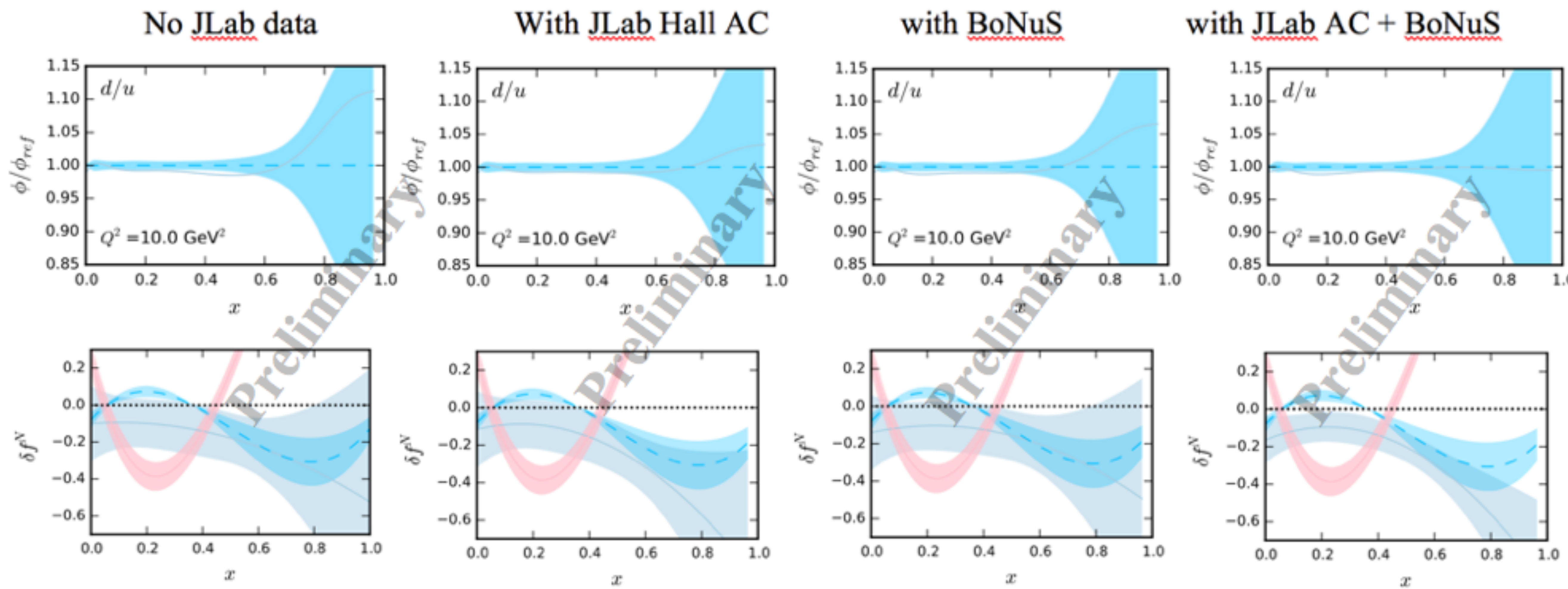

•Calculation with CJ15 PDFs and CJ15 Off-Shell parameters (blue band)
•Calculation with CJ15 PDFs and KP Off-Shell parameters (green line)

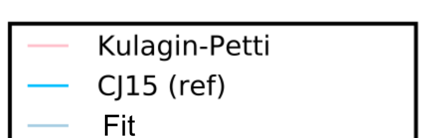
# Impact of JLab 6GeV data on Off Shell




Here we have included the following JLab 6 GeV data sets
Hall A, C data :- jl00106F2[p&d], e06009d, e99118[p&d], jlcee96[p&d], e03103[p&d]
Hall B data :- BoNuS6, clas6

CJ15 (global analysis)



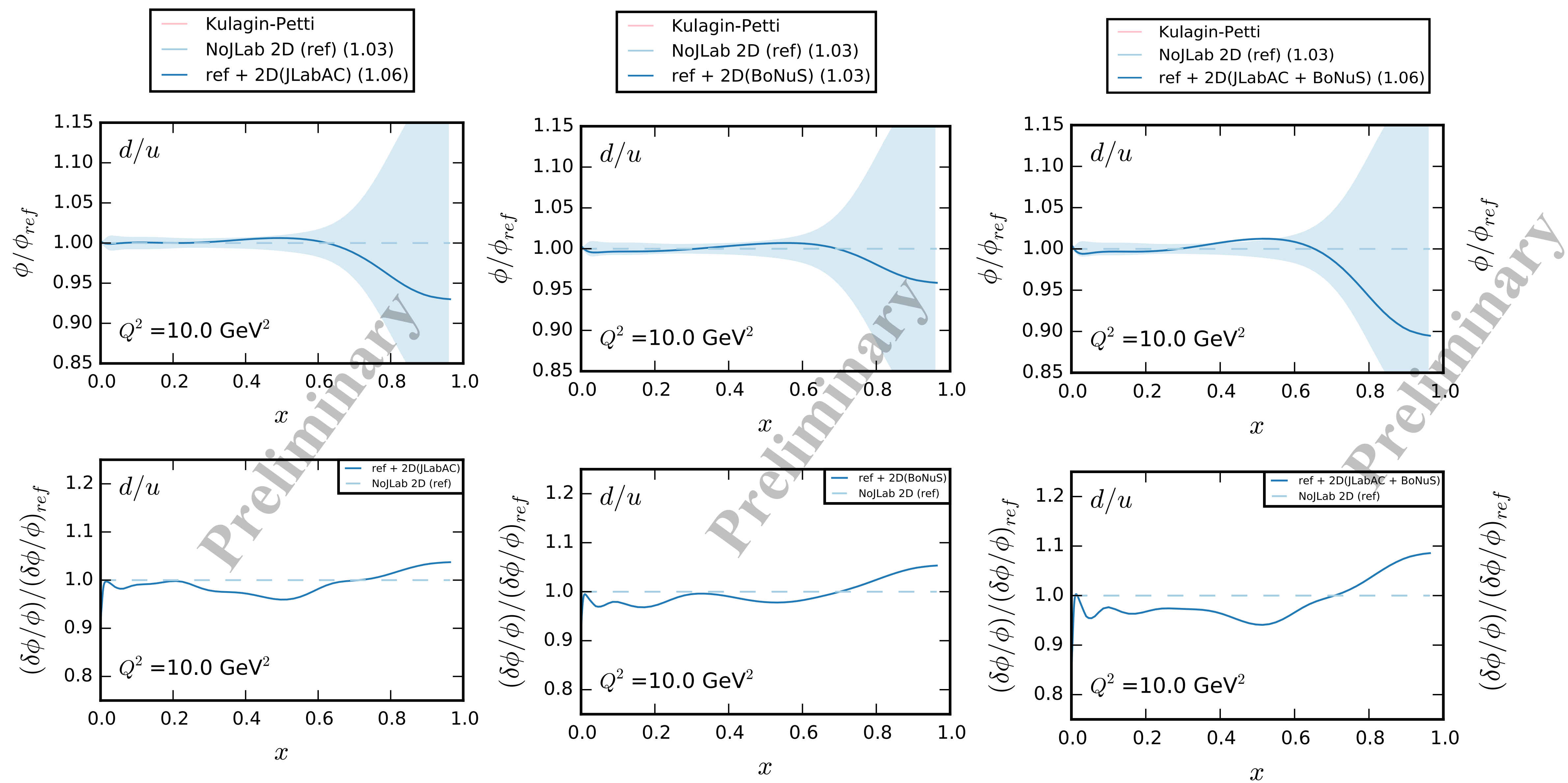

Off-Shell discrepancy between CJ & KP

# Impact of JLab 6GeV data on d/u

Ref + JLab A,C

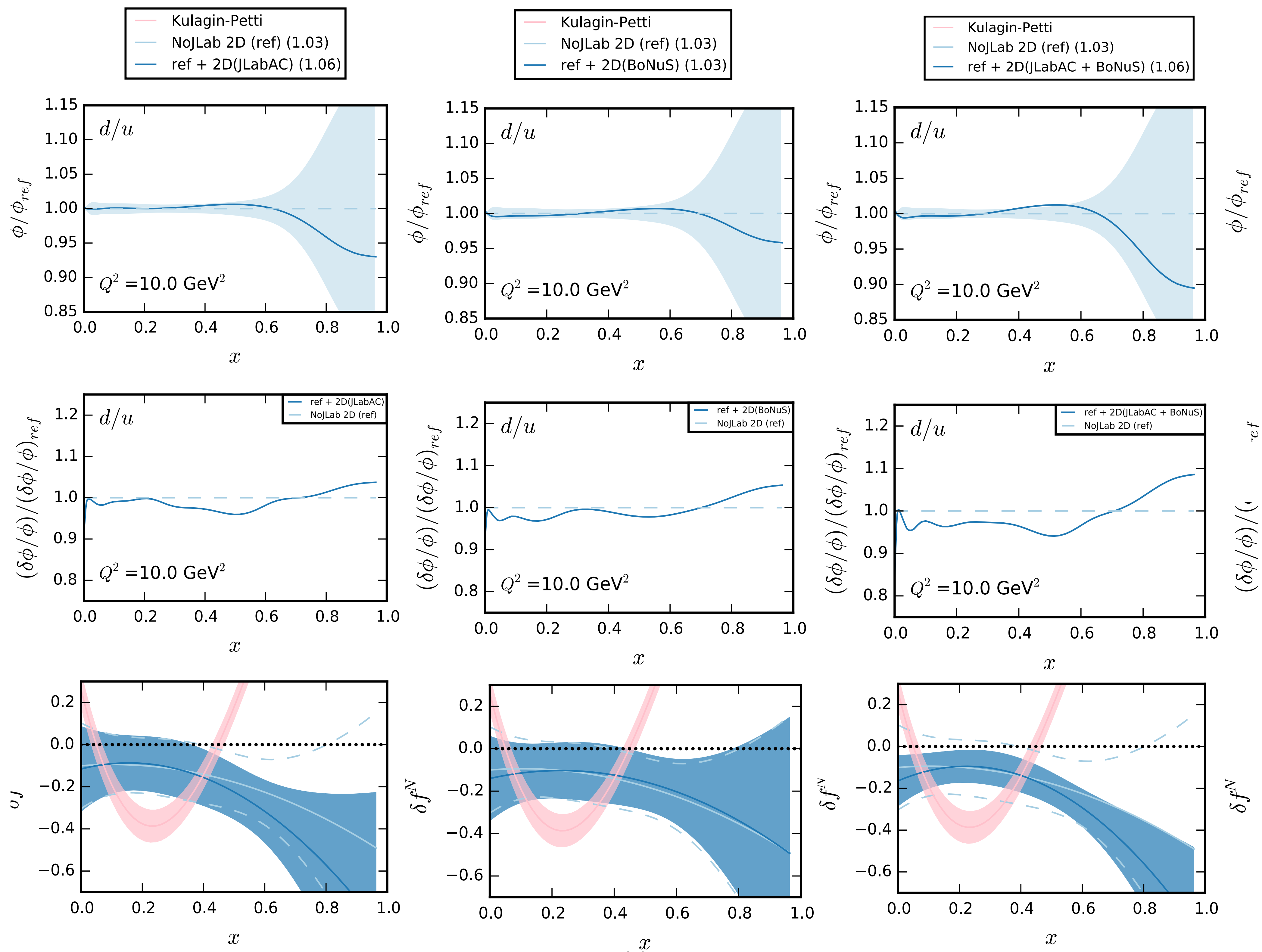
Ref + BoNuS

Ref + JLab AC + BoNuS



# Impact of JLab 6GeV data on d/u and Off-Shell

Ref + JLab A,C | Ref + BoNuS | Ref + JLab AC + BoNuS



# Discussion & Outlook

- Uncertainty of the Off-Shell function gets shrunk with combined JLab A,C + BoNuS, while combining JLab A.C & BoNuS

- There is about ~10% improvement on d/u systematic uncertainty from the entire JLab6 data

- u-quark distribution as well as gluon distribution systematic uncertainties also get improved

- A paper in progress…

*Thank you*